PB-221 641

THE CAPACITY OF THE SOIL AS A NATURAL SINK FOR CARBON MONOXIDE

STANFORD RESEARCH INSTITUTE

PREPARED FOR
COORDINATING RESEARCH COUNCIL, INC.

DECEMBER 1972

Distributed By:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

Final Report

PB 221 641

THE CAPACITY OF THE SOIL AS A NATURAL SINK FOR CARBON MONOXIDE

Prepared for:

COORDINATING RESEARCH COUNCIL
NEW YORK, NEW YORK

CONTRACT CAPA-4-68 (1-71)

and

THE ENVIRONMENTAL PROTECTION AGENCY
DURHAM, NORTH CAROLINA

CONTRACT 68-02-0307

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

43

BIBLIOGRAPHIC DATA SHEET	1. Report No. CRC-APRAC-CAPA-4-68-6	2.	3. Recipient's Accession No. PB-211 611
4. Title and Subtitle: The Capacity of the Soil as a Natural Sink for Carbon Monoxide			5. Report Date: December 1972 6.
7. Author(s): R.B. Ingersoll			8. Performing Organization Rept. No. SRI-LSU-1380-FR
9. Performing Organization Name and Address: Stanford Research Institute, Menlo Park, California 94025			10. Project/Task/Work Unit No. 11. Contract/Grant No. CRC-APRAC-CAPA-4
12. Sponsoring Organization Name and Address: The Environmental Protection Agency, Research Triangle Park, North Carolina, 27711 and the Coordinating Research Council, Inc., 30 Rockefeller Plaza, New York, N.Y. 10020			13. Type of Report & Period Covered: Final Report 14.

15. Supplementary Notes

Not releasable to the public until June 15, 1973.

16. Abstracts

Studies were conducted to determine the potential magnitude of the soils of North America to serve as a sink for atmospheric carbon monoxide. In a series of field studies, soils were exposed in situ to experimental atmospheres containing CO. The influence of environmental factors was studied in the laboratory. The objectives were to (1) determine the potential CO uptake of soils under natural conditions in the major ecological habitats of North America; (2) determine what influence environmental variables exert on the potential CO uptake rates of soils; and (3) estimate the potential of soils of North America to serve as a sink for atmospheric CO.

17. Key Words and Document Analysis. 17a. Descriptors

Carbon Monoxide
Air Pollution
Soil
Atmosphere
Vegetation
Organic Matter

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 7B; 13B; 6m; 8F; 6C; 7C.

18. Availability Statement: Releasable to the General public.	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 43
	20. Security Class (This Page) UNCLASSIFIED	22. Price $3.75

FORM NTIS-35 (REV. 3-72) THIS FORM MAY BE REPRODUCED USCOMM-DC 14952-P72

STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

Final Report *December 1972*

THE CAPACITY OF THE SOIL AS A NATURAL SINK FOR CARBON MONOXIDE

By: R. B. INGERSOLL

Prepared for:

COORDINATING RESEARCH COUNCIL
NEW YORK, NEW YORK

CONTRACT CAPA-4-68 (1-71)

and

THE ENVIRONMENTAL PROTECTION AGENCY
DURHAM, NORTH CAROLINA

CONTRACT 68-02-0307

SRI Project LSU-1380

Approved by:

W. A. SKINNER, *Executive Director*
Life Sciences Division

CONTENTS

INTRODUCTION 1

SUMMARY AND CONCLUSIONS 3

BACKGROUND 5

METHODS AND MATERIALS 8

Field Studies 8
Test Sites 8
Test System 13
Field Gas Analyzing System 14
Test Procedure 14
Laboratory Studies 15
Test System 15
Test Soils and Procedures 15
Water Control 17

RESULTS 18

Field Test Sites 18
Roadside Study 30

DISCUSSION 35

REFERENCES 37

ILLUSTRATIONS

1	Field Test Sites	9
2	Effect of Temperature on the CO Uptake Rate of Potting Soil	23
3	Influence of Agricultural Chemicals on CO Uptake by Soil	29
4	Effect of Continuous CO Exposure on the CO Uptake Rate of Soils	32

TABLES

1	Vegetation Characteristics of Test Sites	10
2	CO Uptake Rates of Soil at Selected Sites Throughout North America	19
3	CO Uptake Rates of Vegetative Areas Corrected for Temperature Variation	21
4	Effects of Temperature on Uptake of Carbon Monoxide by Southern North American Soils under Laboratory Conditions When Exposed to Atmospheres of About 100 ppm CO	25
5	Effect of Soil Moisture on the Uptake of Carbon Monoxide by Potting Soil Exposed to 100 ppm CO at 25°C	26
6	Comparison of the CO Uptake Capacity of Soils Under Cultivation and Soils under Natural Vegetation	27
7	Effect of Type and Quantity of Organic Matter in a Soil on Its CO Uptake Capacity	28
8	Soil Activity at Sites Alongside a 20-Mile Stretch of the Bayshore Freeway Preselected on the Basis of Representative Vegetation or Ground Cover	31
9	Potential CO Uptake Rates of the Soils of the Conterminous United States	33
10	Potential CO Uptake Rates of the Soils of the World	34

INTRODUCTION

For many years, carbon monoxide (CO) has been considered to be an important atmospheric pollutant. Recent estimates indicate that over 400 million metric tons of CO are produced annually due to man's activities alone (6). At this rate of production, the ambient concentration of CO could be expected to double every two to three years; however, ambient levels have apparently not changed appreciably in the last decade (6). The fate of CO liberated into the atmosphere is poorly defined. A number of possible mechanisms for its removal have been postulated with little confirming evidence. Due to the potential health hazard of increased levels of CO and ever-increasing emissions, the search for natural sinks for CO has become a field of increasing interest during the last few years.

A series of research contracts was awarded to Stanford Research Institute by the Coordinating Research Council and the National Air Pollution Control Association (later transferred to the Environmental Protection Agency) to provide insight into the fate of atmospheric CO. The objective was to investigate the biosphere as a possible sink for atmosphere CO. Research conducted under the initial contract by Mrs. Elaine Levy (10) showed that nonsterile soil depleted CO from test atmospheres, whereas steam-sterilized soil did not; this finding suggested a role for soil or soil microorganisms as a sink for CO. During the second year of the study, laboratory experiments conducted by Drs. R. E. Inman and R. B. Ingersoll (5) showed that, potentially, soil had a capacity to serve as a sink for all the CO produced globally and that this activity was due to soil microorganisms--in particular, a number of soil fungi. Estimates of the soil sink potential obtained from that study were based on a limited number of laboratory observations and, since soils were shown to vary widely in their activity, the estimates could be significantly different from the actual potential of soils in their natural state.

The research described in this report, conducted under a third contract, was designed as an extension of the first two studies. The objectives were to:

(1) Determine the potential CO uptake of soils under natural conditions in the major ecological habitats of North America.

(2) Determine what influence environmental variables exert on the potential CO uptake rates of soils.

(3) Estimate the potential of soils of North America to serve as a sink for atmospheric CO.

SUMMARY AND CONCLUSIONS

Studies were conducted to determine the potential magnitude of the soils of North America to serve as a sink for atmospheric carbon monoxide. In a series of field studies, soils were exposed in situ to experimental atmospheres containing CO. The influence of environmental factors was studied in the laboratory. The results are summarized below:

(1) The uptake of CO by soils in situ is highly variable, with rates ranging from 7.5 to 109.0 mg CO/hr/m^2. Generally, the tropical soils were the most active and the desert soils were the least active in CO uptake. The forest soils were generally more active than the grassland soils.

(2) The rate of CO uptake by soils was greatest at a concentration of 100 ppm and decreased as the concentration decreased. This effect was most pronounced for the soils with the slowest rates of CO uptake.

(3) The rate of CO uptake by soils under cultivation was significantly less than that of the same soil under natural vegetation. Laboratory studies indicate that this difference was not due to agricultural chemicals, which have little influence, but was probably due to a lack of organic matter in the cultivated soils, which limited growth of the microflora. The laboratory studies showed that the type as well as the amount of organic matter in a soil significantly influences the CO uptake by that soil.

(4) The uptake rate of soils adjacent to a major highway was greater for soils with a dense surface cover of vegetation than for bare soils. Laboratory studies indicated that soils constantly exposed to high levels of CO have greater CO uptake rates, which could explain what appeared to be higher rates for soils near freeways. The ground cover phenomenon was probably due to increased organic matter in the soil under vegetation.

(5) Soils removed from test sites for testing in the laboratory had much reduced CO uptake rates from those found in the field and did not retain their ranking in relative activity. This was most probably due to the long confinement of the soil in sealed containers during transport and storage.

(6) The uptake capacity of the soils tested in the field was adjusted for temperature variation, using laboratory data, and vegetative regions were assigned the average value of the tests in that region. The CO uptake potential of the soils of the conterminous United States and the world was estimated to be 505 million and 14.3 billion tons/year, respectively.

BACKGROUND

Carbon monoxide is the most widespread and common air pollutant emitted by man's activities. Although ambient concentrations of CO seldom appear to exceed 1 part per million (ppm), especially in remote regions, more CO is produced annually by man than all the other man-made air pollutants combined. Ambient levels of CO vary considerably, probably due to the uneven distribution of man over the surface of the earth and the action of natural sinks. Swinnterton et al. (19) recorded concentrations over the Atlantic Ocean between Chesapeake Bay and Puerto Rico that ranged between 0.075 and 0.44 ppm, with concentrations generally decreasing with increased distance from urban areas. Robinson and Robbins (15) found values of 0.04 to 0.2 ppm over different regions of the Pacific Ocean. Higher concentrations occurred over the northern than over the southern hemisphere, probably due to a larger number of air pollution sources in this hemisphere. Seiler and Junge (17), in a study of the global tropospheric distribution of CO, found the average for the northern hemisphere to be 0.1-0.15 ppm. Robbins et al. (14) measured 0.3-0.9 ppm of CO at ground level in Greenland, 0.8 ppm at one spot on the north coast of California, 0.03-0.3 ppm at Crater Lake, Oregon, and concentrations up to 0.8 ppm at Patrick Point, California. They concluded that the average CO concentration in the northern hemisphere is approximately 0.05 ppm.

Both man-made and natural sources contribute to the ambient CO levels. However, in urban areas the levels of CO are always higher than ambient levels in remote areas and the CO concentration is observed to rise and fall with the intensity of motor vehicle traffic. During a recent study in Los Angeles, the CO level at one station along the Harbor Freeway measured 3 ppm at 4:00 a.m. when traffic intensity was lowest and 15 ppm at 8:30 during the morning rush hour. Similar patterns have been observed in other large metropolitan areas. During prolonged periods of air stagnation, the CO levels in Los Angeles have exceeded 30 ppm for an 8-hour period. In London, CO concentrations at street level on a calm day have reached 360 ppm.

Jaffe (6) has estimated that the world-wide production of CO by man exceeds 400 million metric tons each year. According to Jaffe, over 70% of the CO liberated by man in the United States is due to the burning of gasoline by motor vehicles.

There are also numerous natural sources of CO. The extent to which these may contribute to the total ambient concentration is not yet understood. Recently, it was postulated that the oxidation of atmospheric methane produces 10 times as much CO as do man's activities and that this oxidation is accompanied by atmospheric reaction of CO with hydroxyl radicals, resulting in a large natural sink for CO (13). This large natural turnover of CO due to atmospheric reactions would explain the calculated short lifetime of CO in the atmosphere (23,24). However, some researchers in this field (9) feel that the concentrations of the initial reactants are too low to account for these reactions; in the atmosphere, this theorized CO turnover cycle cannot be substantiated. Swinnerton et al (20) have observed that sea water is supersaturated with CO and that the net gas transport was from the sea to the air. Seiler and Junge (17) found CO concentrations on surface waters to be 10-40 times higher than expected. The ocean has been estimated to be a source of CO varying in magnitude from 5 to 100% of the man-made source (1,20).

The catabolism of haem-like compounds is known to result in CO production within living or autolyzing systems (2). Wilks (25) has shown that macerated tissues of several green plants (most notably, alfalfa) evolve CO. Recently, workers at Argonne Laboratories have suggested, on the basis of isotopic studies, that the decay of chlorophyll may be a source of CO at least one-third as large as the man-made sources (3,12, 18).

The residence time of CO in the atmosphere has been variously estimated. The most recent calculations range from 0.1 to 0.3 years (4,11, 23). This relatively short residence time is circumstantial evidence for the existence of sizable sinks for CO. Jaffe (6) has suggested several possible sinks, including various elements of the biosphere and atmospheric reactions. Seiler and Junge (17), noting a rapid decrease of CO in the tropopause, considered the stratosphere as a major sink for CO due to CO oxidation there by OH, H_2O_2, and HO_2 radicals. Evidence also exists that the atmosphere is a natural source of CO as well as a sink. Swinnerton et al. (21) have found that raindrops may show up to 200-fold supersaturation with CO in respect to attendant atmosphere, and they postulate that the source of CO in this instance is in rain-forming clouds. They suggest, as a plausible CO-formation mechanism, the photo-oxidation of dissolved organic matter in the rain water or the dissociation of CO_2 by electric discharge in storm clouds.

The involvement of the biosphere in the turnover of CO has been postulated for a number of years. In 1926, Wehmer (22) showed that the microbial activity in the soil was capable of reducing the CO content of illuminating gas. However, at that time CO was not known to be a

component of the atmosphere, so no attempt was made to analyze lower concentrations of CO. Several anaerobic methane bacteria are known to oxidize CO to CO_2 in the absence of H_2 or to reduce CO directly to methane in the presence of H_2 (8). In the 1930s, Jones and Scott (7) reported that certain bacteria present in sealed coal mines were capable of removing CO from the mine atmosphere.

In 1969 (5) we postulated that, based on our laboratory experiments, soil is potentially a large sink for atmospheric CO. This study indicated that, potentially, soil could serve as a sink for 6.5 times as much CO as is produced annually by man. Seiler and Junge (17) had made similar observations for garden soil, but gave no estimate of the rate of CO uptake.

Although the literature indicates that CO is involved in various biological mechanisms that could influence its concentration and residence time in the atmosphere, more precise information was needed before the role of the biosphere as a sink for CO could be properly assessed. This report presents data relating to the action of soil in situ in removing CO from experimental atmospheres.

METHODS AND MATERIALS

Studies were conducted in the field over soils in situ at selected test sites, and in the laboratory over amended natural soils or artificial soil mixtures. Field studies comprised an extensive series of tests at selected sites over the North American continent and a separate study of various roadside situations in the lower San Francisco Bay area. Laboratory studies involved the determination of the effects of various soil amendments and treatments on the rate of CO uptake by experimental soils.

Field Studies

Test Sites

The continental field test sites were selected throughout North America to represent as many of the major ecological biotypes as could be tested within the time and funds available. Each site was selected on the basis of its location within a region of a particular type of vegetation. Maps contained in "Potential Natural Vegetation of the Conterminous United States," "Forest Regions of Canada," "Readers Digest Great World Atlas," and "The Odyssey World Atlas"* were used to define the major vegetation regions and select the test sites. Vegetation class or type was used as the major guideline for test site selection because it is a better overall indicator of different ecological situations than any other single environmental parameter, including soil type. The continental field test sites selected are shown on the map in Figure 1 and are characterized in Table 1.

---

*Potential Natural Vegetation of the Conterminous United States. A. W. Küchler. Special Publication #36, American Geographical Society, Washington, D.C., 1964.

Forest Regions of Canada. Canadian Department of Fisheries and Forestry, 1970.

Readers Digest Great World Atlas, The Readers Digest Association, Pleasantville, New York, 1963.

The Odyssey World Atlas. Odyssey Books, New York, 1966.

*Sites where soils under cultivation were tested as well as soils under natural vegetation

FIGURE 1 FIELD TEST SITES

Table 1

VEGETATION CHARACTERISTICS OF TEST SITFS

Vegetation Zone	General Characteristics	Site Number	Dominant Species
Montane Forest	Most extensive and important of western forest climaxes; characterized by dominance of evergreens Pinus ponderosa, Pseudosuga mucronata and Abies concolor, along with other species of Pinus.	E-2	Pinus edulis, Juniperus monosperma
		E-17	P. ponderosa, Pinus contorta
		A-5	P. ponderosa, Pseudosuga taxifolia
		A-5B	P. ponderosa, Pseudosuga taxifolia
		A-6	P. contorta
		E-22	P. contorta
Steppe	Dry dense to medium dense grassland, with generally few woody plants; dominated by Bromus spp., Avena spp., Fescue ssp., Agropyron spp., and Stipa spp.	A-1	Avena fatua, Bromus spp.
		A-1B	Avena fatua, Fescue spp.
		A-2	Stipa cernua
		A-2B	Stipa pulchra
		A-16	Fescue spp., Agropyron spp.
		A-16B	Agropyron spp.
		A-17	Ag. spicatum, F. idahoensis
Temperate Grassland	Grouping of tall, mid and short grass prairies with generally mixed populations of grasses, dominated by species in the genera Stipa, Agropyron, Andropogon, Bromus, Bouteloua, and Bulbilis	A-14	Bulbilis dactyloides
		E-20	Bouteloua gracilis
		M-16	Bouteloua eriopoda
		M-17	Bouteloua eriopoda
		E-3	Bromus spp.
		E-4	Bromus rubens, Poa pratensis
		E-15	Bo. breviseta, An. hallii
		E-21	Opuntia spp., Lupines
Coastal Forest	Westcoastal forest stretching from N. Calif. to British Columbia, with dominance, generally, of douglas fir (Pseudosuga menziesii) and redwoods.	A-3	P. menziesii
		A-4	Tsuga plicata, P. menziesii
		A-18	Tsuga heterophylla, P. menziesii
		A-18B	Tsuga heterophylla, P. menziesii

Table 1 (Continued)

Vegetation Zone	General Characteristics	Site Number	Dominant Species
Southern Flood Plain Forest	Forests on the flood plain of southeastern U.S., with dominance of tupelo (Nyssa sylvatica), oaks (Quercus spp.), and bald cypress (Taxodium distichum)	E-13	T. distichum
Appalachian Forest	Forests covering Appalachian Mountains region; dominated by white oak (Quercus alba) and northern oak (Quercus rubra)	E-10	Q. alba, Fagus grandifolia Betula lenta
		E-5	Q. alba, Q. rubra Carya cordiformis
Southern Mixed Forest	Tall mixed deciduous and evergreen broadleaf and needle leaf in southeastern U.S.; dominated by oaks (Quercus spp.), pines (Pinus spp.), magnolia (Magnolia grandifolia), beech (Fagus spp.), and gums (Liquidamber spp.)	E-18	Quercus alba Quercus laurifolia Pinus taeda
Desert	Major region in southwestern U.S. and northern Mexico; dominated by black brush (Coleogyne ramosissima), greasewood (Sarcobatus vermiculatus), cactus (Opuntia spp.), creosote bush (Larrea divaricatta), and mesquite (Prosopis juliflora)	M-1	L. divaricata, Opuntia spp.
		M-2	L. divaricata, Yucca baccata
		M-3	Bouteloua spp.
		M-4	Acacia spp.
		E-1	Artemisia tridentata
Tropical Rain Forest	Mixed species of a very large number of families.	M-9	Unidentified
		M-9B	Unidentified
		M-13	Unidentified
Tropical Deciduous Forest	Mixed forest of scrub and deciduous trees; dominated by Acacia spp., Albizzia spp., and many trees in the Leguminosae family	M-7	Mimosa, palms, ferns, legumes
		M-10	Leguminous trees, vines, shrubs
		M-11	Leguminous trees, no grasses
		M-15	Opuntia spp., Albizzia spp.

Table 1 (Concluded)

Vegetation Zone	General Characteristics	Site Number	Dominant Species
Broadleaf and Mixed Forest	Large deciduous forest spreading over much of northeastern U.S.; dominated by associations of maple (Acer) - Beech (Fagus), oak (Quercus)-chestnut (Castanea) and oak (Quercus) - hickory (Carya), with occasional stand of pine (Pinus)	E-8	Acer spp., Quercus spp.
		E-12	Quercus spp., Carya spp., Pinus fp
		E-5	Quercus spp., Carya
		E-7	Carya ovata, Quercus spp.
		E-10	Quercus spp.
		E-11	Quercus spp., Carya spp., Pinus ssp
		E-19	Quercus spp., Carya spp., Fraxinus spp.
Boreal Forest	Broad band of forest lying just south of the tundra; dominated by aspens (Populus), birches (Betula), and pines (Pinus)	A-9	Populus tremuloides
		A-10	Populus tremuloides
		A-11	Populus tremuloides
		A-12	Pinus banksiana
		A-12B	Pinus banksiana
		A-13	Pinus banksiana
Tropical Grassland	Grasslands ranging from those with no woody species to those with scattered shrubs (Acacia) and legumes dominated by grasses (Graminae) and sedges (Cyperaceae)	M-8	Numerous unidentified grasses and small mints
		M-14	Numerous unidentified grasses, legumes, wild citrus
		M-15B	Numerous unidentified grasses and small sedges
Tundra	Artic tundra ground cover on areas of extreme winters; dominated by sedges, grasses, forbs, lichens and mosses	A-7	Curex - Cladonia spp.
		A-7B	Curex - Cladonia spp.
		A-8	Curex - Cladonia spp.

Other factors that determined the exact location of each site in a region were the availability of accurate weather information for the site and the accessibility of the site. Test sites were selected where major roads approached the weather station sites found in the Klimadiagramm Weltatlas.* Also, wherever possible, the sites were chosen in areas where a comparison of a given soil under natural vegetation could be made with the same soil under cultivated or agronomic conditions.

In addition to the continental field test sites, 12 roadside sites were selected along the Bayshore Freeway (Highway 101) in California between Menlo Park and San Jose. The sites were selected along both sides of the freeway in areas where different types of vegetation were planted as ground cover, or in fields adjacent to the freeway. These roadside test sites are described in Table 8.

Test System

A bottomless, gas-tight field atmospheric chamber (FAC) positioned over the soil to be tested in situ was used to contain the test atmosphere. The FAC was collapsible, consisting of a rigid base and top, with flexible sides for easy storage and transport. The base was constructed of four aluminum plates, each 10" × 36" × 5/16". The base of the FAC was forced or dug into the soil to a depth of 4-6 inches to provide a good seal with the soil surface. The collapsible sides attached to the base were constructed of fiberglass cloth backed with neoprene rubber on the inside, making it gas-tight, and aluminized on the outside to reflect light and help prevent heat build-up inside the chamber. The top was constructed of 3/4" plywood, with a thin sheet of aluminum on the outer surface; the inner surface was painted with white enamel. A squirrel-cage fan was attached to the top inside the chamber to provide circulation of the enclosed atmosphere. Support rods were used to hold the chamber top up when the chamber was expanded for testing. The volume of the chamber was about 0.9 m^3 when in testing position. Ports in the base provided access for probes to monitor temperature during testing and for the inlet and outlet lines from the gas analyzer.

---

*Klimadiagramm Weltatlas, Walter and Lieth, Gustav Fisher Verlag, Jena, 1967.

Field Gas Analyzing System

The concentration of CO in the FAC was monitored nondestructively and continuously by a Beckman Infrared Gas Analyzer Model 315B and a recorder. Chamber gas was pumped out through tubing and passed through a column of drierite, then pumped through the analyzer and returned to the FAC. The flow rate was maintained at 2 liter/minute during testing. The IR gas analyzer was calibrated using ambient air as zero and 100 ppm CO as the up-scale calibration gas before each test. The analyzer was located in a mobile laboratory unit provided by modifying a Winnebago 22-ft "motor inn".

Test Procedure

The continental field sites were reached by means of the mobile field laboratory. Test equipment included drying and weighing instruments for soil moisture determinations, a pH meter, and the field IR-test chamber system for monitoring CO uptake by soils in situ. The vehicle was also equipped with living accommodations for the research personnel. This mobile laboratory provided the capacity to reach and test CO uptake by soils in areas, some of which were rather remote, throughout the continent.

The actual test sites were selected by visual inspection of the region preselected on the map. Sites were selected to be representative of the vegetation type characteristics of the region. Natural vegetation (e.g., small shrubs, grasses, and herbs) was left intact on the test site as the FAC was positioned over the soil to be tested. To begin a test, the concentration of CO in the FAC was brought to ~95 ppm by injecting pure CO into the chamber. The level of CO in the chamber was continuously monitored during a two- to four-hour test period. Results were expressed as the average milligrams of CO removed from the test atmosphere by the test soil per hour per square meter of soil surface. A total of 59 continental sites were tested. During the test period, the moisture content of the soil and the soil pH were determined. Soil moisture was determined by weighing duplicate 10-g samples before and after oven-drying them at 250°F for two hours and cooling them in a desiccator. The percent weight loss was calculated to be the percent moisture. The pH was determined on a soil slurry of 10 g of soil and 20 ml of water.

The same test procedure was used to determine the uptake potential of soils at the 12 selected roadside sites in the lower bay region south of Menlo Park, California.

Laboratory Studies

Test System

Experimental soils were contained in 250- or 1000-ml filter flasks or in plastic atmospheric chambers (PACs) of 11 liters capacity which were described in previous reports. The side arms of the filter flasks and PACs were used to introduce test atmospheres and to remove atmospheric samples for analysis. Temperatures were controlled by placing the containers in an environmental growth chamber or incubator. Analysis of atmospheric samples removed periodically from atmospheres over the test soils was conducted via gas chromatography, using a Varian Aerograph unit and a flame ionization detector. The procedure involved the catalytic reduction of CO to methane, as described in previous reports to this client.

To begin a test, the container with soil was flushed with the test atmosphere containing the desired concentration of CO. After a period suitable to achieve constant CO concentration within the container, flushing was terminated, the container was sealed, and the test period was begun. Samples of the test atmosphere (usually 1 ml) were removed at "zero time" and at various intervals following the beginning of the test and were analyzed to monitor CO concentrations. A Hamilton, gas-tight hypodermic syringe was used to remove samples for analysis.

Test Soils and Procedures

A potting soil mixture consisting of loam, sand, leaf mold, peat moss and steer manure (25:25:16.6:16.6:16.6) was used as the base test soil in all experiments except those involving organic matter variables. Also, soil samples taken at various continental test sites were used in the laboratory to study effects of temperature variables on CO uptake rates.

Effects of soil moisture on CO uptake activity were studied using 50 g of the base soil mixture contained in 250-ml filter flasks. Starting with air-dried soil, sufficient water was added to the respective samples in duplicate to establish a series of soil moisture levels. Soils so amended were incubated at 30°C for 24 hours prior to testing at 30°C.

Studies of temperature effects on CO uptake rates were conducted on soil samples taken at field test sites visited during the southern portion (Mexico and southwestern United States) of the field testing phase of the research. These samples were collected at the time field tests were conducted at the respective field sites, and were placed in sealed one-gallon tins for storage and transport to the laboratory. Hence, microbial balances and soil conditions existing at the time these soil samples were tested in the laboratory could not be considered as characteristic of conditions prevailing in the field at the time the samples were taken. A soil sample volume of 50 ml contained in a 250-ml filter flask was incubated at the test temperature for 24 hours prior to testing. Test temperatures were 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40° and 45°C, maintained by a series of incubators and water baths. The control consisted of the base potting soil. Following incubation, the test soils were exposed to a test atmosphere containing an initial concentration of 100 ppm CO, and uptake rates at the test temperatures were monitored during test periods ranging from 2 to 4 hours. The length of the test period used for a given temperature treatment depended largely on the rapidity with which the soil depleted atmospheric CO at that temperature--the slower the rate of depletion, the longer the test period.

Effects of amending the base soil with selected agricultural chemicals on CO uptake rates were studied in 250-ml filter flasks. One-kilogram sample of potting soil were treated with 100 ml of one of the following:

Triox - (1.86%) 2-methoxy-4,6-bis(isopropyl amino s-triazine)
(<1%) parachlorophenol and other chlorinated phenols (11 ml/100 ml)

Benlate - (50%) benomyl(methyl 1-(butylcarbamoyl)-2-benzimidazole carbamate (0.2 g/100 ml)

Isotox - (5%) gamma benzene hexachloride
(10%) p,o-dimethyl dithiophosphate of diethyl mercaptosuccinate
(5%) dichloro diphenyl trichloroethane
(3%) 2,4,5-tetrachlorodiphenyl sulphone
(20%) aromatic petroleum solvent (0.4 ml/100 ml)

Diazinon - (25%) 0,0-diethyl-0-(2-isopropyl-4-methyl-6-pyrimidinyl
(57%) aromatic petroleum solvent (0.26 ml/100 ml)

Fungicide - (25%) pentachloronitrobenzene
(25%) N-trichloromethylthio-4-cyclohexene-1,2-dicarboximide
(10%) zinc ethylene bisdithiocarbamate (0.37 g/ml)

The soil samples were thoroughly mixed and allowed to equilibrate and dry for 24 hours. They were again thoroughly mixed, and 50-g aliquots were taken from each and placed in 250-ml flasks, with four replicates per treatment. The soils were held at 30°C and tested for their uptake rate after 2, 6, 7, 8, 10, 14, and 22 days of incubation.

Organic matter amendments of a base soil consisting of loam and sand (50:50) were studied for possible effects on CO uptake. A 5-kg sample of base soil was amended (8% and 25% by weight) with commercial preparations of peat moss, steer manure, and leaf mold and maintained in PACs at 10% soil moisture level during the course of the tests. Uptake activity by the various soils was monitored over a period of 9 weeks at 25°C. During the intervals between tests, the soils were maintained at 25°C in an incubator, with the PAC lids placed askew over the soils to provide for aeration. Tests were conducted by sealing the lids in place, flushing the PACs for 5 minutes with the test atmosphere containing initially 100 ppm CO, then sealing the PACs and monitoring CO concentrations over a 2- to 4-hour test period.

The effects of constant exposure to soil to various levels of CO on the rate of CO uptake by soil was studied using 175-g samples of the base soil in 1000-ml filter flasks. Duplicate flasks were continually flushed (100 ml/min) with a test atmosphere containing 0, 5, 28, or 100 ppm CO. The gas stream was bubbled through a water column prior to entry into the flasks to prevent excessive drying of the soil during the flushing process. Soils were maintained at their original moisture content (ca. 10%) by daily weighings, and were held at 25°C throughout the test period, which lasted for 45 days. Uptake capabilities of the test soils exposed to different CO levels were determined every 2 to 3 days via the usual procedure as described above, and changes in uptake capabilities were plotted over time.

RESULTS

Field Test Sites

The CO uptake rates of the soil at selected sites throughout North America are presented in Table 2. The sites are listed according to their map coordinates, and designated by numbers preceded by M for sites in the U.S. Southwest and Mexico, A for those in the U.S. Pacific Northwest and Canada, and E for those in the remainder of the United States. As can be readily seen, the CO uptake rates measured in the field showed a great deal of variation, ranging from 7.5 to 109 $mg/hr/m^2$. Although soils with low pH and moderate moisture content tended to be more active in CO uptake, there were a great many exceptions. Table 3 shows the uptake rates when corrected for the changes in temperature throughout the year. These corrections were made by comparing the field rate to the laboratory rate shown in Figure 2. The following equation was used to make the corrections.

$$C = R \cdot \frac{rmt}{rft} \cdot \frac{m}{12}$$

where C is the corrected value, R is the observed field value, rmt is the rate of uptake on Figure 2 for the average yearly temperature for the test site, rft is the rate of uptake on Figure 2 of the temperature during the actual field test, and m is the number of months during the year when the temperature at the test site averages above 0°C

This correction is an approximation based on fluctuations of the test temperature above and below the average temperature for the site, since each site could be visited only once and the temperature during testing was limited to whatever it happened to be at the time of testing. Althougn the surface temperature of the soil in many areas warms to above freezing during the day in months in which the average monthly temperature is below freezing and therefore some CO uptake may occur, there are also nights in months in which the average temperature is above freezing but the soil temperature may be 0°C or below. These two would tend to balance each other out. As can be seen from the values in Tables 2 and 3, the soils tested at the higher latitudes were most influenced by this correction, since the testing in these areas was all done in the summer months

Table 2

CO UPTAKE RATES OF SOIL AT SELECTED SITES THROUGHOUT NORTH AMERICA

Site No.	Location	Vegetation Type	Field CO Uptake ($mg/hr/m^2$)	Soil pH	Soil Moisture (%)	Air Temperature (°F)
M1	Gila Bend, Ariz.	Desert scrub	8.7	8.3	8.1%	75
M2	El Paso, Tex.	Desert scrub	9.6	8.1	6.2	54
M3	Chihuahua, Chi.	Desert scrub	24.6	7.1	3.3	57
M4	Durango, Dur.	Desert scrub	9.2	6.4	2.0	75
M5	Etla, Oax.	Montane forest	24.1	5.8	11.4	71
M7	Santo Domingo, Oax.	Tropical deciduous forest	74.6	6.8	16.4	77
M8	Palengue, Chi.	Equatorial grassland	28.8	5.6	3.9	85
M9A	Palengue, Chi.	Tropical rain forest	14.0	7.7	54.9	79
M9B	Palengue, Chi.	Tropical rain forest	28.3	7.8	24.5	78
M10	Champoton, Camp.	Tropical deciduous forest	35.1	7.7	14.6	91
M11	Merida, Yuc.	Tropical deciduous forest	43.1	7.7	23.3	83
M13	Minatitlan, V.C.	Tropical rain forest	58.0	6.8	30.0	79
M14	Poza Rica, V.C.	Equatorial grassland	13.5	7.6	32.3	81
M15	Tampico, V.C.	Tropical deciduous forest	83.5	7.9	20.8	78
M15B	Tampico, V.C.	Equatorial grassland	109.0	7.9	20.2	80
M16	Monterrey, N.L.	Equatorial grassland	21.1	--	17.1	66
M17	Fort Stockton, Tex.	Grassland	14.6	--	4.0	70
E1	Winnemucca, Nev.	Sagebrush	7.5	7.4	1.6	92
E2	Monticello, Utah	Montane forest	15.6	7.7	2.0	79
E3	Douglas, Wyo.	Mixed prairie	43.2	7.6	7.1	88
E4	Sabetha, Kans.	Tall grass prairie	30.4	7.6	11.0	85
E5	Columbia, Mo.	Oak-hickory forest	38.2	7.4	24.5	83
E7	Athens, Ohio	Mixed deciduous forest	47.8	4.9	20.0	78
E8	Binghamton, N.Y.	Deciduous forest	43.6	6.3	33.6	88
E10	Harrisburg, Pa.	Appalachian oak	19.8	4.8	30.7	71
E11	Charlottesville, Va.	Mixed deciduous forest	20.6	3.9	45.8	81
E12	Columbus, Ga.	Deciduous forest	33.3	4.9	10.0	79
E13	Shreveport, La.	Flood plain forest	36.9	7.7	30.5	71
E14	Wichita Falls, Tex.	Grassland	41.3	7.8	16.8	91
E15	Albuquerque, N.M.	Grassland	15.4	8.0	0.2	84
E17	Donner Pass, Calif.	Montane forest	17.6	5.2	33.2	63
E18	Mt. Olive, Miss.	Southern mixed deciduous forest	15.2	6.2	24.0	79
E19	Stonelick, Pa.	Oak-hickory forest	29.1	5.4	23.5	68
E20	Prairie View, Kans.	Bluestem prairie	24.3	7.9	4.6	78
E21	Egbert, Wyo.	Mixed prairie	45.4	6.7	2.5	88
E22	Yellowstone Pk., Wyo.	Montane forest	30.5	5.8	16.5	55
A-1	Stockton, Calif.	California steppe	16.8	7.6	2.5	88
A-2	Red Bluff, Calif.	California steppe	10.5	5.5	0.1	94
A-2B	Red Bluff, Calif.	California steppe	13.0	7.2	1.9	84
A-3	Grants Pass, Ore.	Coastal forest	30.2	6.4	6.0	68

Table 2 (Concluded)

Site No.	Location	Vegetation Type	Field CO Uptake ($mg/hr/m^2$)	Soil pH	Soil Moisture (%)	Air Temperature (°F)
A-4	Bellingham, Wash.	Coastal forest	51.8	5.7	16.9%	71
A-4B	Bellingham, Wash.	Coastal forest	25.8	5.2	15.5	74
A-5	Prince George, B.C.	Montane forest	38.4	6.4	14.2	72
A-5B	Prince George, B.C.	Montane forest	26.0	6.0	30.0	67
A-6	Watsons Lake, Yuk.	Montane forest	28.0	5.2	59.0	59
A-7	Haines Junction, Yuk.	Tundra	29.7	5.6	27.0	63
A-7B	Haines Junction, Yuk.	Tundra	22.0	5.8	2.4	43
A-8	Haines Junction, Yuk.	Tundra	20.3	5.9	41.0	56
A-9	Grouard, Alb.	Boreal forest	36.6	5.8	17.8	77
A-10	McMurray, Alb.	Boreal forest	44.6	6.3	34.0	72
A-11	St. Walburg, Sask.	Boreal forest	32.0	6.4	--	69
A-12	LaRonge, Sask.	Boreal forest	19.6	4.9	3.6	76
A-12B	LaRonge, Sask.	Boreal forest	20.6	4.8	3.8	78
A-13	Hudson Bay, Man.	Boreal forest	17.3	5.9	4.2	72
A-14	Moosejaw, Sask.	Grassland	39.2	8.1	11.7	85
A-15	Fort Benton, Mont.	Mixed prairie	35.5	7.5	22.0	96
A-16	Spokane, Wash.	Steppe	21.3	6.6	3.4	89
A-16B	Spokane, Wash.	Steppe	34.2	7.3	7.1	99
A-17	Burns, Ore.	Steppe	12.8	7.2	2.0	89
A-18	Prince Rupert, B.C.	Coastal forest	24.0	5.2	25.7	62

Table 3

CO UPTAKE RATES OF VEGETATIVE AREAS CORRECTED FOR TEMPERATURE VARIATION

Vegetation Type	Site #	Corrected Rate (mg CO/hr/m^2)	Average Rate (mg CO/hr/m^2)
Montane forest	E-2	5.67	7.74
	E-17	10.76	
	A-5	2.63	
	A-5B	4.15	
	A-6	7.70	
	E-22	15.55	
Steppe	A-1	4.03	3.38
	A-1B	5.29	
	A-2	3.98	
	A-2B	3.07	
	A16	3.37	
	A-16B	3.18	
	A-17	0.77	
Temperate grassland	A-14	2.71	3.81
	E-20	2.24	
	M-16	8.77	
	M-17	3.75	
	E-3	3.93	
	E-4	3.60	
	E-14	11.86	
	E-15	3.10	
	D-21	1.96	
Coastal forest	A-3	14.05	8.84
	A-4	8.09	
	A-18	9.39	
	A-18B	3.81	
Southern flood plain	E-13	26.25	26.25
Appalachian forest	E-10	17.48	13.82
	E-5	10.16	
Southern mixed forest	E-18	3.81	3.81
Desert	M-1	1.89	5.45
	M-2	6.58	
	M-3	11.36	
	M-4	6.86	
	E-1	0.56	

Table 3 (Concluded)

Vegetation Type	Site #	Corrected Rate (mg CO/hr/m^2)	Average Rate (mg CO/hr/m^2)
Tundra	A-7	7.04	5.42
	A-7B	4.83	
	A-8	4.41	
Tropical rain forest	M-9	17.64	35.49
	M-9B	35.65	
	M-13	53.17	
Tropical deciduous forest	M-7	64.81	48.72
	M-10	33.43	
	M-11	40.19	
	M-15	56.44	
Southern conifer forest	E-13	26.25	22.28
	E-18	8.31	
Broadleaf and mixed forest	E-8	26.16	13.87
	E-12	10.07	
	E-5	10.16	
	E-7	21.33	
	E-10	17.48	
	E-11	2.59	
	E-19	9.25	
Boreal forest	A-9	4.17	5.64
	A-10	6.78	
	A-11	6.86	
	A-12	5.36	
	A-12B	5.63	
	A-13	3.71	
Tropical grassland	M-8	23.28	39.07
	M-14	78.41	
	M-15B	15.52	

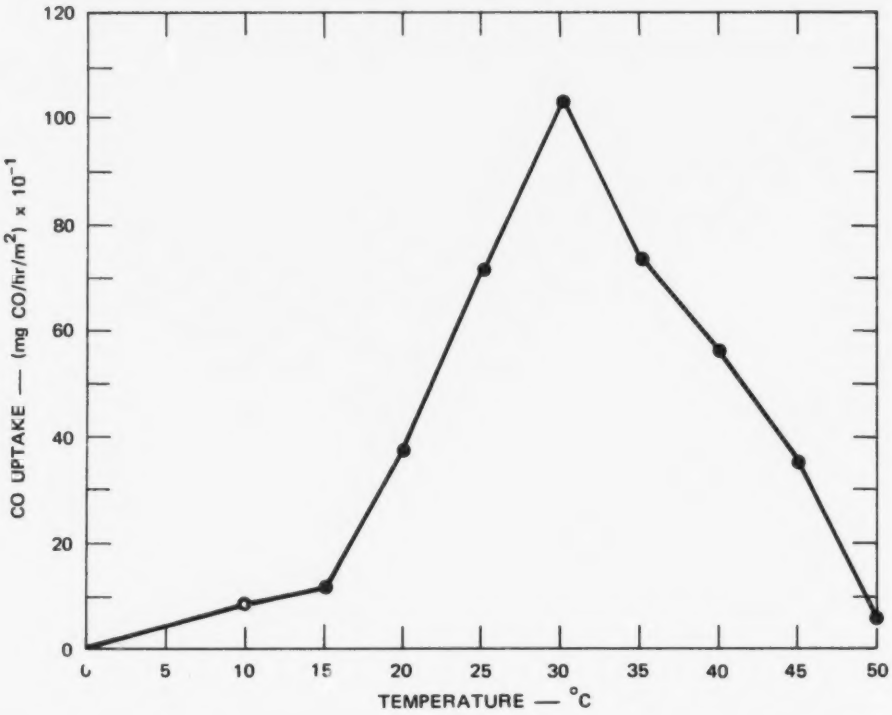

FIGURE 2 EFFECT OF TEMPERATURE ON THE CO UPTAKE RATE OF POTTING SOIL

when the temperature was well above the average and uptake rates were probably near maximum.

The corrections for temperature were based on the laboratory studies on potting soil, diagrammed in Figure 2. Originally it was hoped that these corrections could be based on the laboratory studies of the soil samples collected in the field at each test site. The results of the first study of this kind are shown in Table 4. There was no correlation between the values found in the field and those obtained in the laboratory. Rates of CO uptake by soils in the laboratory were much lower than the rates observed in the field, and soils that were most active in the field were not always the most active in the laboratory. This discrepancy was probably due to changes in the soil microflora during the trip back to the laboratory, during which time the soil samples were stored in the sealed cans. Because of this lack of correlation, it was decided to use the data from the study on potting soil for all the corrections.

No correction was made for soil moisture since the laboratory study on the influence of soil moisture on the CO uptake rate (Table 5) shows that the rate is only affected at very high and low moisture contents and the regions of extreme moisture (e.g., the tropical rain forest, >50%) and low moisture (deserts, <5%) generally always have more or less the same moisture content.

Wherever possible, field test sites were chosen at locations where two tests could be made for comparison--one on the soil under natural vegetation and the other on the same soil under cultivation. The results of this testing program are shown in Table 6. In all cases, the cultivated soils were significantly less active than the corresponding soils under natural vegetation. The average uptake rates for the natural and cultivated soils were 11.7 and 2.6, respectively.

It was suspected that the lack of organic matter in the agricultural soil might be the reason for the lower activity of that soil. Hence, a study on the influence of organic matter in soil was conducted. The results of this study (Table 7) show that both the amount and type of organic matter in a soil influence the CO uptake rate of a soil. Soils containing leaf mold or steer manure had higher CO uptake rates than soils containing peat moss. These rates are low compared to rates found in some of the active natural soils.

It was also suspected that the treatment of agricultural fields with chemicals such as herbicides and fungicides might be the reason for the lower CO uptake. Therefore, a laboratory study (Figure 3) was done on that parameter. All the compounds were applied in their recommended

Table 4

EFFECTS OF TEMPERATURE (°C) ON UPTAKE OF CARBON MONOXIDE ($mg/hr/m^2$)
BY SOUTHERN NORTH AMERICAN SOILS UNDER LABORATORY CONDITIONS
WHEN EXPOSED TO ATMOSPHERES OF ABOUT 100 ppm CO

Location	5	10	15	20	25	30	35	40	45
Gila Bend	0.27	0.0	-0.58	0.11	1.10	0.25	-0.80	0.10	1.22
El Paso	1.24	1.60	2.36	3.91	2.86	5.52	8.57	4.48	3.03
Chihuahua	0.59	0.25	0.19	-0.16	0.65	0.04	-1.72	0.35	0.97
Durango	0.46	0.0	0.42	0.08	-0.38	0.16	0.0	-1.15	-0.03
Oaxaca (Etla)	1.53	1.30	2.31	5.44	3.99	7.37	6.52	6.17	6.26
Santa Domingo	1.37	1.84	3.96	2.48	6.29	7.79	8.44	8.75	6.15
Palenque (Tepa)	0.72	1.07	0.21	1.37	2.24	4.29	4.28	3.94	1.77
Palenque	0.70	1.49	3.91	2.27	3.71	4.39	6.75	2.60	3.47
Palenque	2.52	3.98	6.78	9.22	9.13	15.36	11.54	12.67	8.49
Champoton	0.76	1.93	2.54	3.71	2.79	5.49	5.54	5.44	4.49
Merida	1.69	2.17	5.04	6.11	7.17	14.93	10.45	10.37	6.21
Minatitlan	2.22	2.90	4.00	7.18	6.73	11.37	11.77	9.46	11.01
Posa Rica	2.59	3.18	5.42	10.49	7.79	9.02	11.25	9.33	6.73
Tampico	0.60	3.56	2.93	5.49	4.17	6.36	8.63	8.42	6.77
Tampico	-0.33	0.92	0.07	0.44	1.16	1.13	3.48	2.25	2.13
Monterrey	0.89	1.33	2.76	2.26	5.71	7.99	7.38	6.34	4.39
Ft. Stockton	0.34	0.28	1.24	0.94	1.99	1.60	0.75	1.75	1.33
Ft. Stockton	0.45	1.18	1.32	2.27	3.10	2.97	3.94	2.78	4.65

Table 5

EFFECT OF SOIL MOISTURE ON THE UPTAKE OF CARBON MONOXIDE BY POTTING SOIL EXPOSED TO 100 ppm CO AT 25°C

Soil Moisture (%)	CO Uptake ($mg/hr/m^2$)*
5	6.44
10	7.01
16	7.08
19	7.00
22	7.04
28	6.64

*Average of 3 replicates.

Table 6

COMPARISON OF THE CO UPTAKE CAPACITY OF SOILS
UNDER CULTIVATION AND SOILS UNDER NATURAL VEGETATION

	Soils Under Natural Vegetation		Soils Under Cultivation	
Test Site	Vegetation Type	Rate*	Type	Rate*
Grouard, Alb.	Boreal forest	4.2	Plowed field	1.1
Athens, Ohio	Mixed deciduous forest	21.3	Plowed field	3.4
Ft. McMurray, Alb.	Boreal forest	6.8	Plowed field	2.4
Chenango, N.Y.	Deciduous forest	26.2	Plowed field	1.8
Wichita Falls, Tex.	Grassland	11.9	Wheat stubble	7.5
Regina, Sask.	Grassland	2.7	Plowed field	1.6
Van Meter, Mo.	Oak-hickory forest	10.2	Newly planted milo field	2.9
Shrevesport, La.	Flood plain forest	26.3	Plowed field	4.3
Sabetha, Kans.	Grassland	3.6	Milo stubble	2.9
Grants Pass, Ore.	Coastal forest	14.1	Plowed field	2.2
Cincinnati, Ohio	Oak-hickory forest	21.3	Fallow field	3.4
Prairie View, Kans.	Bluestem prairie	2.3	Plowed field	1.2

* $mgCO/hr/m^2$, corrected for annual average temperature at test sites.

Table 7

EFFECT OF TYPE AND QUANTITY OF ORGANIC MATTER
IN A SOIL ON ITS CO UPTAKE CAPACITY

Organic Treatment	Organic (%)	Average CO Uptake ($mg/hr/m^2$) After: 2 Weeks	4 Weeks	9 Weeks
Leaf mold	0	9.03	7.47	14.50
	8	13.30	19.13	23.53
	25	27.94	30.22	28.01
Peat Moss	0	10.74	9.46	20.97
	8	10.17	15.86	20.90
	25	13.65	12.23	15.71
Steer Manure	0	8.03	8.53	20.69
	8	13.51	16.57	24.74
	25	21.09	21.47	25.03

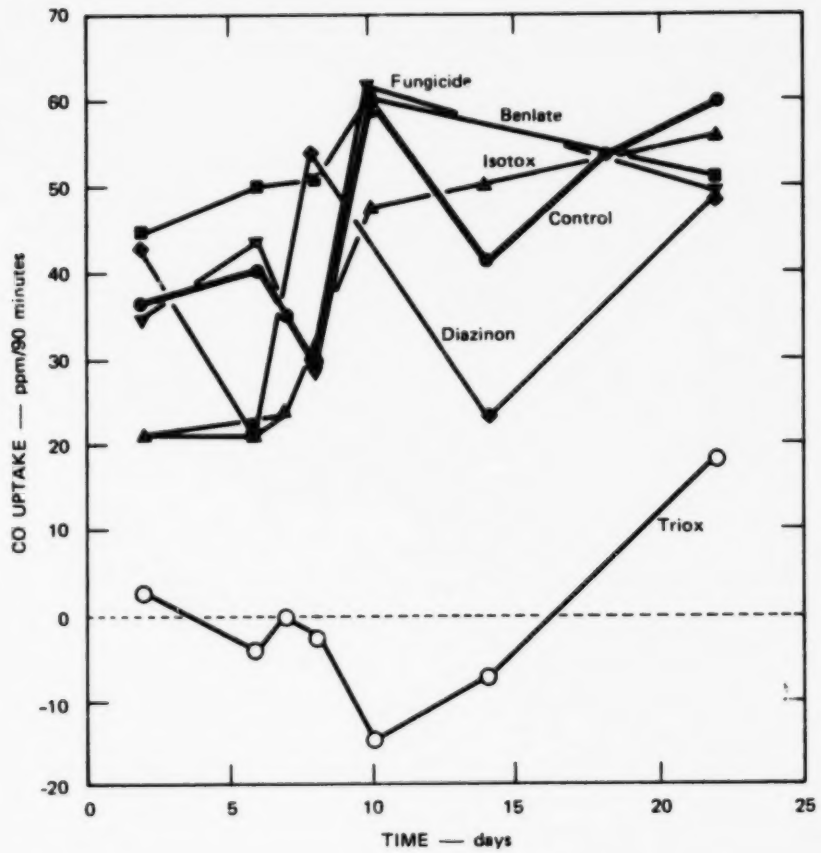

FIGURE 3 INFLUENCE OF AGRICULTURAL CHEMICALS ON CO UPTAKE BY SOIL

dosages. Only Triox, a vegetation-killer containing pentachlorophenol and prometone, was effective in reducing the soil CO uptake capacity, and after a period of three weeks it appeared that even the soil treated with Triox was resuming its capacity to take up CO.

Roadside Study

Since soils alongside roads and, in particular, major highways are constantly exposed to high levels of CO, a study on the rates of CO uptake by these soils was conducted. Table 8 depicts the results of this study. In general, soils that were covered by a ground cover (e.g., ice plant, ivy, or grass) had higher CO uptake rates. All the soils had generally higher rates than soils would be expected to have at that latitude. To test the hypothesis that the constant exposure of these soils to CO was responsible for the high rates, a laboratory experiment was performed in which soils were constantly exposed to various levels of CO and their CO uptake capacity was monitored for several weeks. As shown in Figure 4, soils exposed to 100 and 28 ppm CO developed higher rates of CO uptake than did soils exposed to 5 ppm or to ambient air (control). The rate for the soil exposed to 5 ppm was only slightly higher than that for the control soil.

Tables 9 and 10 summarize the CO uptake potential of the soils of the conterminous United States and the world. The values of CO uptake for the various vegetative regions were averaged and corrected for temperature variations, then multiplied by the area of that region. The respective totals for the U.S. and the world potential uptake rates are 505 million and 14.3 billion tons annually. An inspection of these two tables indicates that, potentially, the forest regions of the United States could serve as major sinks due to the large proportion of the area they cover and, on a global basis, the tropical regions are potentially the largest sinks due to high year-round uptake rates.

Table 8

SOIL ACTIVITY AT SITES ALONGSIDE A 20-MILE STRETCH OF THE BAYSHORE FREEWAY (US 101) PRESELECTED ON THE BASIS OF REPRESENTATIVE VEGETATION OR GROUND COVER

Test Site	Vegetation	CO Uptake ($mg/hr/m^2$)	Avg. Temp.* (°F)	Soil pH	Soil Moisture† (%)
Embarcadero Road interchange	Iceplant	64.5	65	7.6	19.6
San Antonio Road interchange	Iceplant	47.9	85	7.8	5.7
Mathilda Avenue interchange	Ivy	52.5	66	8.2	3.9
W. Bayshore Road‡	Ivy	43.0	60	8.3	19.2
Frontage Road‡	Grass	63.4	69	7.8	10.0
Dirt road‡	Barley	32.7	81	7.6	2.5
San Tomas Expressway interchange	Grass	36.9	80	7.4	5.1
Trimble Road interchange	Grass	17.8	76	8.0	7.3
U.S. 85 interchange	Bare	22.6	95	7.7	6.1
Mathilda Avenue off-ramp	Bare	16.2	82	7.7	3.7
W. Bayshore Road‡	Plowed	23.1	77	7.0	4.2
W. Bayshore Road‡	Plowed	15.0	71	8.7	3.5

*Soil temperature inside test chamber.

†Percent moisture of surface soil.

‡Site off freeway right-of-way, but within 100 ft of freeway.

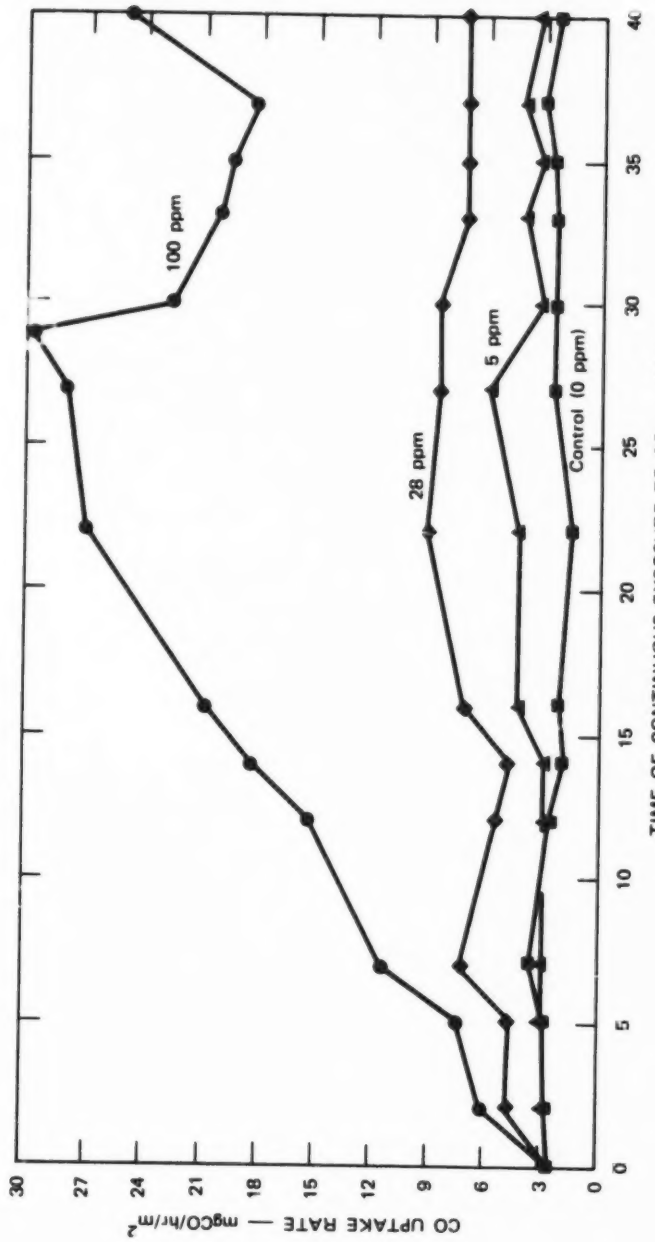

FIGURE 4 EFFECT OF CONTINUOUS CO EXPOSURE ON THE CO UPTAKE RATE OF SOILS

Table 9

POTENTIAL CO UPTAKE RATES OF THE SOILS
OF THE CONTERMINOUS UNITED STATES

Soil-Vegetation Type	Area* (mi^2)	CO Uptake† (tons/yr/mi^2)	Total CO Uptake (tons × 10^6/yr)
Cropland	468,000[a]	86.0	40.25
Pasture	616,674[a]	179.3	110.57
Coastal forest	329,390[b]	200.7	83.93
Deciduous forest	339,485[b]	254.8	86.50
Montane forest	87,150[b]	242.0	21.10
Southern mixed forest	48,644[b]	86.5	4.21
Appalachian forest	265,519[b]	313.7	84.17
Southern flood plain forest	58,782[b]	595.0	34.95
Sagebrush steppe	264,867[b]	76.7	20.32
Sagebrush	145,047[b]	52.2	19.09
Desert scrub	220,723[b]		
Paved roads	28,100[c]	0	0
Covered area	26,500[d]	0	0
Lakes, rivers, etc.	78,267[d]	0	0
Total	2,977,128		505.12

*Areas based on figures found in: (a) Statistical Abstract of the United States, 1971, 92nd Ed., U.S. Department of Commerce, Washington, D.C.; (b) Map of U.S. Forests, U.S. Geological Survey; (c) 1969 Highway Statistics, U.S. Department of Transportation, Washington, D.C.; (d) 1971 World Almanac, Newspaper Enterprise Assoc., Inc., New York, N.Y.

†Corrected for annual temperature variations.

Table 10

POTENTIAL CO UPTAKE RATES OF THE SOILS OF THE WORLD

Soil-Vegetation Type	Area (10^6 mi^2)*	Average CO Uptake† (tons/yr/mi^2) × 10	Total CO Uptake (tons × 10^6/yr)
Agricultural	4.60	86.0	395.4
Pasture	1.84	179.3	329.7
Tropical grassland	3.45	886.9	3,062.5
Temperate grassland	3.10	86.5	268.4
Steppe	3.45	76.7	264.5
Montane forest	4.66	175.7	817.8
Taiga forest	4.71	127.5	600.9
Mixed and broadleaf forest	1.32	254.8	410.0
Southern pine forest	0.29	505.8	145.2
Tropical deciduous forest	1.78	1,105.9	1,969.6
Tropical rain forest	6.55	805.6	5,277.5
Tundra	1.15	123.0	141.3
Desert	10.86	52.2	567.0
Covered by ice, water, roads, structures, etc.	9.20	0	0
Total	56.96		14,250.0

*Areas based on figures derived by integrating vegetation areas found in map types of natural vegetation in Readers Digest World Atlas (pp. 146 and 147) and the 1971 World Almanac.

†Corrected for annual temperature variations.

DISCUSSION

The potential rates of CO uptake by the soils of the United States and the world are estimated in this report to be 505 million and 14.3 billion tons per year, respectively. These rates are based on studies conducted at a uniform exposure of 100 ppm CO and are thus an estimate of the potential of the soil if exposed to this high level of CO. Recent laboratory studies by Seiler (16) indicate that the rate of CO uptake by soils exposed to an ambient level of CO (0.2 to 1.0 ppm) is one-tenth of the values obtained in this study. The actual CO uptake rates for the soils of the United States and the world are thus probably somewhere around 50 and 1.4 billion tons of CO annually--still a considerable fraction of the estimated annual 407 million tons of CO produced by man globally.

The higher CO uptake rates for the soils in tropical regions of Mexico are quite probably due to the higher microbial populations in these soils due to favorable climate and high amounts of organic matter in these soils. The rates of CO uptake in the tropical rain forests were somewhat lower than expected, probably due to the high moisture content of this soil, which may have limited diffusion of the gas. Also, the rates in the arctic tundra were somewhat higher than expected, indicating that the microbial populations in these soils increase during the summer months when this soil warms.

The uptake of CO by agricultural soils was, in all cases, much lower than the uptake rate for the same soil under natural vegetation. This was most probably due to a lack of organic matter in the surface layer of soils that are cultivated.

A study on the influence of agricultural chemicals, another suspected cause of the reduced activity in cultivated soils, indicates that these chemicals have only a minor effect, if any at all.

The study alongside the freeway in California indicates that the uptake rate is highly dependent on the ground cover over it. This is quite probably due to an increase in organic matter and friability of soils with luxuriant ground cover, thus leading to a more active microfloral population in the soil. Prolonged gassing studies conducted in the laboratory indicate that soils that are constantly exposed to CO concentrations above 5 ppm have relatively high CO uptake capacities. Soils

alongside the freeway are constantly exposed to higher than ambient levels of CO, and this may explain why they appear to be slightly more active in CO uptake, on the average, than other soils tested. Since soils alongside freeways are exposed to CO at higher levels on a more or less continuous basis, the rate of uptake of CO by these soils is increased due to the higher starting levels of CO and also probably due to an induced higher uptake rate for the soil.

An interesting aspect of this study is the evolution of CO by soils treated with Triox during the first two weeks after treatment. This is consistent with findings in previous studies that soils sterilized by autoclaving evolved CO. Studies by Seiler and Junge have indicated that at very low levels of atmospheric CO (<0.2 ppm), an equilibrium is established over a soil where CO uptake equals CO evolution by the soil. Thus, while soils on a net basis are a large sink for CO, they also quite probably are a natural source for CO as well. Information on the character of this CO equilibrium would help to answer questions that arise when isotope determinations are used to calculate the sources of CO in the atmosphere and the residence time of CO in the atmosphere.

It also appears from the roadside studies that the capacity of the soil to remove CO from the atmosphere is inducible, since soils adjacent to a major highway appeared to have higher than normal CO uptake rates and laboratory studies showed soils exposed continuously to 100 ppm CO developed a CO uptake rate almost 10 times that of soils exposed to CO-free air. This indicates that soils in areas of high ambient CO such as the Los Angeles Basin may be contributing more as a CO sink than other soils.

It is clear from this study that the CO picture in respect to soils is a highly variable and complex one and that future studies on the CO equilibrium and CO uptake at ambient levels of CO should be conducted.

REFERENCES

1. Anonymous. Isotopic study confirms CO sources. Chem. Eng. News 50, 2 (1972).

2. Coburn, R. F. (Ed.). Biological effects of carbon monoxide. Ann. N.Y. Acad. Sci. 174, 1-430 (1970).

3. Crespi, H. L., D. Huff, H. F. DaBoll, and J. J. Katz. Carbon Monoxide in the Biosphere: CO Emissions by Fresh Water Algae. Final Report CRC-APRAC-CAPA-4-68-5 (1972).

4. Dimitriades, B., and M. Whisman. Carbon monoxide in lower atmosphere reactions. Environ. Sci. Tech. 5, 219-222 (1971).

5. Inman, R. E., R. B. Ingersoll, and Elaine A. Levy. Soil: A natural sink for carbon monoxide. Science 172, 1229-1231 (1971).

6. Jaffe, L. S. Carbon monoxide in the biosphere: sources, distribution, and concentrations. Symposium on "Sources, Sinks, and Concentrations of Carbon Monoxide and Methane in the Earth's Environment," St. Petersburg Beach, Florida, August 1972.

7. Jones, C. W., and G. S. Scott. Carbon monoxide in underground atmospheres. The role of bacteria in its elimination. Ind. Eng. Chem. 31, 775-778 (1939).

8. Kluyver, A. J., and Ch. G.T.P. Schueller. On the fermentation of carbon monoxide by pure cultures of methane bacteria. Arch. biochem. 14, 57-70 (1947).

9. Kummler, R. H., M. H. Bortner, and L. S. Jaffe. Carbon monoxide in lower atmosphere reactions. Environ. Sci. Technol. 5, 1140-1141 (1971).

10. Levy, Elaine A. The biosphere as a possible sink for carbon monoxide emitted to the atmosphere. Final Report, Project PSU-7888, Stanford Research Institute, Menlo Park, California, 1970.

11. Levy, H., II. Normal atmosphere: Large radical and formaldehyde concentrations predicted. Science 173, 141-143 (1971).

12. Maugh, T. H., II. Carbon monoxide: natural sources dwarf man's output. Science 177, 338-339 (1972).

13. McConnell, J. C., M. B. McElroy, and S. C. Wofsey. Natural sources of atmospheric CO. Nature 233, 187-188 (1971).

14. Robbins, R. C., K. M. Borg, and E. Robinson. Carbon monoxide in the atmosphere. J. Air Pollution Control Assoc. 18, 106-110 (1968).

15. Robinson, E., and R. C. Robbins. Atmospheric carbon monoxide in the north and south Pacific Ocean areas. Submitted for publication in J. Geophys. Res., 1971.

16. Seiler, W. Carbon monoxide in the atmosphere. Symposium on "Sources, Sinks, and Concentrations of Carbon Monoxide and Methane in the Earth's Environment," St. Petersburg Beach, Florida, August 1972.

17. Seiler, W., and C. Junge. Carbon monoxide in the atmosphere. J. Geophys. Res. 75, 2217-2226 (1970).

18. Stevens, C. M., L. Krout, D. Walling, A. Venters, A. Engelkemeir and L. E. Ross. The Isotopic Composition of Atmospheric Carbon Monoxide Earth and Planetary Sci. Letters 16, 147-165 (1972).

19. Swinnerton, J. W., V. J. Linnenbon, and C. H. Cheek. Distribution of methane and carbon monoxide between the atmosphere and natural waters. Environ. Sci. Tech. 3, 836-838 (1969).

20. Swinnerton, J. W., V. J. Linnenbon, and R. A. Lamontagne. The ocean: a natural source of carbon monoxide. Science 167, 984-986 (1970).

21. Swinnerton, J. W., R. A. Lamontagne, and V. J. Linnenbon. Carbon monoxide in rainwater. Science 172, 943-945 (1971).

22. Wehmer, C. Biochemishe Zersetzung des Kohlenoxyds. Chem. Ber. 59, 887-890 (1926).

23. Weinstock, B. Carbon monoxide: Residence time in the atmosphere. Science 166, 224-225 (1969).

24. Weinstock, B. and H. Niki. Carbon Monoxide Balance in Nature. Science 176; 290-293 (1972).

25. Wilks, S. S. Carbon monoxide in green plants. Science 129, 964-966 (1959).